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Research Paper

The thermal effect of heating two-phase closed thermosyphons on the high-speed railway embankment in seasonally frozen regions

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HIGHLIGHTS

- The work mechanism of HTPCT is studied firstly in seasonally frozen regions.
- The heating performance of HTPCTs applied to the embankment of high-speed railway is evaluated.
- The HTPCT could effectively reduce the freezing depths and is recommended to be used in engineering in cold regions.

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ABSTRACT

The heating two-phase closed thermosyphon (HTPCT), as a highly efficient heat transfer device, can be used to warm embankments in seasonally frozen regions. The HTPCT is driven by the combination of solar energy and electric heating. In this paper, to evaluate the heating performance of the HTPCTs applied to the embankment of high-speed railway in seasonally frozen regions, a three-dimensional coupled heat transfer model was developed based on the heat and mass transfer theories and the principle of HTPCT, then the thermal property of the embankment with HTPCT was simulated by this model for 10 years according to geology and atmospheric temperature conditions. The numerical results show that: (1) the freezing depth of the normal embankment is larger than that of natural ground surface; (2) the HTPCTs are effective to adjust and increase the geo-temperature of the embankment in cold seasons, and could greatly reduce the freezing depth in the central part of the embankment under the concrete track plate; (3) the effective heating area of the HTPCT is limited, and the freezing depths under the shoulders and slope toes of the embankment are still larger than that under the track plate.

1. Introduction

The two-phase closed thermosyphon (TPCT) is a highly efficient heat transfer device that works by utilizing phase change latent heat of the working fluid within the fully sealed pipe, whose effective thermal conductivity exceeds that of the copper 200–500 times [1]. Due to the high efficiency of heat transfer and simple structure, TPCTs have been widely used in many fields including petrochemical industry [2], solar energy utilization [3–6], nuclear power engineering [7], etc. Furthermore, the TPCT has also been used to cool down the subgrade and foundation to ensure the stability of the infrastructures in permafrost regions. The engineering practices, for example, the Alaska Oil Pipeline Project from the Arctic Ocean to the Pacific Ocean [8,9], Hudson Bay Railway of Canada [10,11], the Qinghai-Tibet Railway [12–14], Qinghai-Tibet Highway [12,15], Chaidaer-Muli Railway [16], Qinghai-Tibet Power Transmission Line(QTPTL) [17,18] have shown that the underlying permafrost could be protected effectively and the freezing-thawing damages could also be alleviated or eliminated. In addition, some experiments [19–21] indicate that if combined with other engineering methods, the cooling effect of the TPCT could be enhanced greatly.

All the above research results are the applications of TPCT in permafrost embankment engineering. But in China, the seasonally frozen regions account for 53.5% of the land area [22]. With the development of economy, high-speed railways are being constructed and some passenger lines have been operated or are being carried out in the seasonally frozen regions in China. In these regions, the high-speed railways are subjected to freeze-thaw cycles, and the frost heave of

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subgrade is a key factor in determining the stability and safety of the railways. Therefore, it is crucial to solve the frost heaving problems of high-speed railway embankment in seasonally frozen regions.

Previous researchers [23,24] mainly changed the frost heaving susceptibilty of subgrade fills within the freezing depths to solve the frost heaving damages. Now, based on the idea of "active heating embankment" [25], we could warm embankments to reduce the freezing depths, and then the frost heave could be weakened or even eliminated by using a heating two-phased closed thermosyphon (HTPCT). The HTPCT is a new type of HTPCTs developed on the basis of the TPCT. The HTPCT is still composed of evaporator section, adiabatic section and the condenser section. The condenser section is inclined upward into the subgrade at a desired angle, and the evaporator section with the form of pipe bundle is placed on the embankment slope, which is helpful to be exposed under solar radiation. The HTPCT obtains heat energy at the evaporator section by the combination of solar heating and electric heating, and then transfers the heat energy into the subgrade soil layers under the concrete track plate to ensure that the subgrade soil layers are not frozen and the frost heaving is reduced.

More recently, numerical studies have been carried out to predict and evaluate the heat transfer performances and cooling effects of TPCTs and thermal insulation layer in engineering projects of cold regions. Pan et al. [26] developed a coupled heat transfer model between soil and TPCTs by using a thermal resistance method to simulate the heat transfer characteristics of TPCTs. Zhang et al. [9,27] improved the thermal resistance model to simulate the cooling effects of TPCTs in the Qinghai-Tibet Railway, and also to evaluate the thermal stability of a shallow tunnel with a TPCT group in the Qinghai-Tibet Plateau. Pei et al. [28] developed a three-dimensional coupled air-TPCT-soil heat transfer model to assess the geothermal conditions of three cases affected by the shady-sunny slope effect. Because the thermal insulation layer has a smaller thermal conductivity and could increase the thermal resistance of structure [29], Wen et al. [8] added thermal insulation to the thermosyphon embankment, and proposed that the combination of insulation and thermosyphon could provide better protection on the permafrost by numerical studies. Mu et al. [30] used a coupled heat transfer model for the air-TPCT-soil system and insulation boards to simulate the long-term thermal characteristics of foundation soils of shallow footings along the Qinghai-Tibet Power Transmission Line. These research findings are significant to evaluate and predict the working performance of TPCT, and could promote the application of TPCT in the future.

These previous numerical studies all focused on the permafrost regions. However, the research of HTPCT applied to the embankment of high-speed railway in seasonally frozen regions has not been reported. In this paper, at first, we established a three-dimensional coupled heat transfer model among atmosphere, HTPCTs and the subgrade soil layers for high-speed railways based on the heat and mass transfer theories and the principle of HTPCT [25]. Subsequently, the thermal characteristics of two embankments with and without HTPCTs on the HDPDL (Harbin-Dalian Passenger Dedicated Line), in seasonally frozen regions, were simulated for 10 years to evaluate the adjusting and control performance of the HTPCTs for geothermal states of high-speed railway embankment.

2. Physical and mathematic model

2.1. Work mechanism of HTPCT

The physical configuration of HTPCT is shown in Fig. 1. It can be seen that the HTPCT is divided into three sections: evaporator section, adiabatic section and condenser section. The HTPCT has the similar heat transfer characteristics to TPCT. Namely, the working liquid (such as ammonia) in the evaporation section absorbs the heat energy produced by solar and electric heating and vaporizes through the adiabatic section to the condenser section under the vapor pressure. In the condenser section, the vapor condenses on the wall, releasing latent heat energy of vaporization, and returns to the evaporator under gravity. The point A, shown in Fig. 1, is taken as control point under the center of concrete track plate at the lower boundary of the well-graded gravel layer. In detail, when the temperature at the point A is higher than the desired value, which can be set according to air temperature in the fields, the embankment is only heated by solar heating with the power of 60 W [25]. When the temperature at the control point is lower than the desired value, the electric heating mode starts up automatically and heats the embankment combined with solar heating simultaneously, to reduce the freezing depth and to alleviate or eliminate the frost heaving of embankment so that the deformation of the embankment meets the requirement of high-speed railways.

2.2. Mathematic model of the HTPCT embankment

(1). HTPCT

Based on the working mechanism of TPCT [9,25,26], the circuit diagram of HTPCT's resistance is shown in Fig. 2, and all kinds of resistances of HTPCT can be expressed as $R_1 - R_4$:

where T_s, T_{ci} and T_{cl} are the temperatures of subgrade fillings, inner wall and working liquid of the condenser section, respectively; T_{vl}, T_{vi} and T_{vo} are the temperatures of working liquid, inner and outer walls of the evaporator section, respectively.

(a). For condenser section ($R_1 + R_2$):

R_1 is the heat resistance of the HTPCT wall, defined as:

$$R_1 = \frac{1}{2\pi\lambda L_c}\ln\left(\frac{d_{oc}}{d_{ic}}\right) \tag{1}$$

where L_c is the length of condenser section; d_{oc} and d_{ic} are the outer and inner diameters of the condenser section, respectively.

R_2 is the heat resistance of the liquid film, defined as:

$$R_2 = \frac{1}{\pi d_{ic} L_c h_c} \tag{2}$$

where, $h_c = 0.925\left(\frac{\lambda_f^3\rho_l^2 gl}{\mu q_c L_c}\right)^{1/3}$, l is the latent heat of working liquid.

(b). For evaporator section ($R_3 + R_4$):

R_3 is the total heat resistance of the liquid film part and liquid pool part, defined as:

$$R_3 = \frac{1}{\pi d_{ie} L_e h_e} \tag{3}$$

where: $h_e = 0.32\left(\frac{\rho_l^{0.65}\lambda_l^{0.3}c_{pl}^{0.7}g^{0.2}q_e^{0.4}}{\rho_v^{0.25}l^{0.4}\mu_l^{0.1}}\right)\left(\frac{P_{sat}}{P_a}\right)^{0.3}$

R_4 is the heat resistance of the HTPCT wall, defined as:

$$R_4 = \frac{1}{2\pi\lambda L_e}\ln\left(\frac{d_{oe}}{d_{ie}}\right) \tag{4}$$

where L_e is the length of evaporator section; d_{oe} and d_{ie} are the outer and inner diameters of the evaporator section, respectively.

The total heat flux Q of the HTPCT is:

$$Q = \frac{T_s - T_{ci}}{R_1} = \frac{T_{ci} - T_{cl}}{R_2} = \frac{T_{vl} - T_{vi}}{R_3} = \frac{T_{vi} - T_{vo}}{R_4} = \frac{T_s - T_{vo}}{\sum R_i} \tag{5}$$

Based on the principle of heat balance, the heat energy absorbed at the evaporator section of the HTPCT is equal to that transferred into the subgrade soil layers at the condenser section without considering the heat loss. Thus, the coupled heat transfer model between HTPCTs and soil layers can be expressed as: